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Effects of interstellar and solar wind ionized helium on the interaction of the solar wind with the local interstellar medium

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ABSTRACT

The Sun is moving through a warm (∼6500 K) and partly ionized local interstellar cloud (LIC) with a velocity of ∼26 km/s. Recent measurements of the ionization of the LIC (Wolff et al., 1999) suggest that interstellar helium in the vicinity of the Sun is 30-40 % ionized, while interstellar hydrogen is less ionized. Consequently, interstellar helium ions contribute up to 50% of the total dynamic pressure of the ionized interstellar component. Up to now interstellar helium ions have been ignored in existing models of the heliospheric interface. In this paper we present results of a new model of the solar wind interaction with the interstellar medium, which takes into account interstellar helium ions. Using results of this model we find that the heliopause, termination and bow shocks are closer to the Sun when compared to the model results that ignore He ions. The influence of interstellar helium ions is partially compensated by solar wind alpha particles, which are taken into account in our new model as well. Finally, we apply our new model to place constraints on the plausible location of the termination shock.

Subject headings: Sun: solar wind — interplanetary medium — ISM : atoms

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1. Introduction

The solar wind interacts with the local interstellar cloud to form the heliospheric interface, which separates the pristine interstellar medium from the unperturbed solar wind. The solar wind meets the interstellar charged component at the heliopause (HP), where the solar wind pressure balances the pressure of the LIC. Since the solar wind is a supersonic flow, the heliospheric termination shock (TS) should be formed to make the solar wind subsonic before it reaches the heliopause. Because the interstellar flow is also supersonic ($V_{LIC} \sim$ 26 km/s, $T_{LIC} \sim$ 6500 K), a bow shock may be formed in the interstellar medium. The idealized structure of the heliospheric interface is shown in Figure 1.

Theoretical studies of the heliospheric interface began more than four decades ago. Recent models of the heliospheric interface take into account the multi-component nature of both the LIC and the solar wind The LIC consists of at least five components: plasma (electrons and protons), hydrogen atoms (and other less abundant atomic species), interstellar magnetic field, galactic cosmic rays, and interstellar dust. The heliospheric plasma includes solar wind particles (protons, electrons, alpha particles, etc.), pickup ions and anomalous cosmic rays (ACRs), which are pickup ions believed to be accelerated to high energies at the termination shock. To construct a realistic theoretical description of the heliospheric interface, one needs to choose a specific approach for each interstellar and heliospheric components (see, e.g., Baranov and Malama, 1993; Alexashov et al.,2000; Fahr et al., 2000; Myasnikov et al., 2000; Izmodenov et al., 2003; for review, see also, Zank, 1999). Up to now, interstellar ionized helium ions were ignored in the multi-component modeling of the solar wind interaction with the LIC. Recent measurements of interstellar helium atoms (Witte et al., 2002) and interstellar He pickup ions (Gloeckler and Geiss, 2002) inside the heliosphere as well as of the interstellar helium ionization (Wolff et al., 1999) allow us to estimate the number density of interstellar helium ions to be 0.008-0.01 cm^{-3}. Current estimates of proton number density in the LIC fall in the range of 0.04 - 0.07 cm^{-3}. Since helium ions are four times heavier than protons the dynamic pressure of the ionized helium component is comparable to the dynamic pressure of the ionized hydrogen component. Therefore, interstellar ionized helium cannot be ignored in the modeling of the heliospheric interface. In this paper we present results of our new model, which for the first time takes into account interstellar ionized helium. Simultaneously with interstellar ionized helium we took into account solar wind alpha particles, which constitute 2.5 - 5 % of the solar wind and, therefore, produce 10 - 20 % of the solar wind dynamic pressure.

2. Model

In this work we start with the global model of the heliospheric interface developed by the Moscow group (Baranov and Malama, 1993, Izmodenov et al., 1999; Alexashov et al., 2000; Myasnikov et al., 2000; Izmodenov and Alexashov, 2003; Izmodenov et al., 2003; see, also, for review Izmodenov, 2001) and introduce interstellar ionized helium (He^+) and solar wind alpha particles (He^{++}) into the model. We consider all plasma components (electrons, protons, pickup ions, interstellar helium ions, and solar wind alpha particles) as one-fluid with the total density ρ and bulk velocity v. This one-fluid approximation assumes that all ionized components have the same temperature T. Although this assumption cannot be made in the case of the solar wind, the one-fluid model is based on mass, momentum and energy conservation laws and predicts plasma bulk velocity and locations of the shocks very well.

The plasma is quasineutral, i.e. $n_e = n_p + n_{He^+}$ for the interstellar plasma and $n_e = n_p + 2n_{He^{++}}$ for the solar wind. We ignore the magnetic field. While the interaction of interstellar H atoms with protons by charge exchange is important, for helium ions the process of charge exchange is negligible due to small cross sections for charge exchange of helium atoms. Hydrodynamic Euler equations for the charged component are solved self-consistently with the kinetic equation for interstellar H atom component. Governing equations for the charged component are:

$$
\begin{aligned}
\frac{\partial \rho}{\partial t} + div(\rho \vec{v}) &= q_1, \\
\frac{\partial \rho \vec{V}}{\partial t} + div(\rho \vec{v}\vec{v} + p\hat{I}) &= \vec{q}_2 \\
\frac{\partial E}{\partial t} + div([E+p]\vec{v}) &= q_3
\end{aligned}
\tag{1}
$$

Here ρ is the total density of the ionized component, p is the total pressure of the ionized component, $E = \rho(\varepsilon + \vec{v}^2/2)$ is the total energy per unit volume, $\varepsilon = \frac{p}{(\gamma-1)\rho}$ is the specific internal energy. The temperature of the plasma is determined from the equation of state $p = 2(n_p + n_{He^+})kT$ for the interstellar plasma and $p = (2n_p + 3n_{He^{++}})kT$ for the solar wind. To calculate sources of mass, momentum and energy into the charged component due to charge exchange of H atoms with protons and photo-ionization and electron-impact-ionization processes we need to know n_p in addition to the total plasma density. (Expressions for the sources can be found, for example, in Izmodenov and Alexashov, 2003.) We solve the continuity equations for He^+ in the interstellar medium and for alpha particles in the solar wind. Then proton number density can be calculated as $n_p = (\rho - m_{He}n_{He})/m_p$. Here n_{He} denotes the He^+ number density in the interstellar medium, and He^{++} the number density in the solar wind. The velocity distribution of H atoms $f_{\mathrm{H}}(\vec{r}, \vec{w}_{\mathrm{H}}, t)$ is calculated

from the linear kinetic equation introduced in Baranov & Malama (1993). The plasma and neutral components interact mainly by charge exchange. However, photo-ionization, solar gravitation, and radiation pressure, which are taken into account in the governing equations, are important at small heliocentric distances. Electron-impact ionization may be important in the inner heliosheath, the region between the termination shock and the heliopause.

3. Boundary conditions

The boundary conditions are the following. At the Earth orbit we assume that solar wind is spherically symmetric, which makes our model axisymmetric, and we use IMP 8 data averaged over several solar cycles for the solar wind parameters: $n_{p,E} = 7.39$ cm^{-3}, $V_{sw,E}$= 432 cm^{-3}. The number density of solar wind alpha particles is varied in our calculations from 0 % to 4.5 % of the solar wind proton number density. The total density and pressure of the solar wind at the inner boundary at 1 AU are then:

$$\rho_E = m_p n_{p,E} + m_{He} n_{He^{++},E}$$

$$p_E = (2n_{p,E} + 3n_{He^{++},E})kT_E.$$

Among the interstellar parameters influencing the heliospheric interface structure, the LIC velocity relative to the Sun and the temperature of the local interstellar gas are now well established by direct measurements of interstellar helium atoms with the GAS instrument on Ulysses (Witte et al., 2002). Unlike interstellar hydrogen, atoms of interstellar helium penetrate the heliospheric interface nearly undisturbed, because of negligible strength of the coupling with protons due to the small cross sections of elastic collisions and charge exchange. Based on these measurements we take in this paper the temperature of the interstellar gas to be 6500 K and the speed of the LIC relative to the Sun as 26.4 km/s. The remaining three input parameters required to calculate the heliospheric interface structure are the number densities of interstellar protons, $\mathrm{n}_{p,LIC}$, of interstellar helium ions, $n_{He^+,LIC}$, and of H atoms, $\mathrm{n}_{H,LIC}$. To find good estimates of these important LIC parameters we use (1) our measurements of the atomic H density at the TS (=0.100 ± 0.008 cm^{-3}), (2) measurements of the LIC atomic He density (= 0.015 ± 0.002 cm^{-3}) (Gloeckler and Geiss, 2001; Witte, private communication), (3) the standard universal ratio of the total H to He, $(\mathrm{n}_{p,LIC}+\mathrm{n}_{H,LIC})/(\mathrm{n}_{He^+,LIC}+\mathrm{n}_{He,LIC}) = 10$, and (4) measurements of the local interstellar helium ionization fraction, $\mathrm{n}_{He^+,LIC}/(\mathrm{n}_{He^+,LIC}+\mathrm{n}_{He,LIC}) = 0.35 \pm 0.05$ (Wolff et al., 1999). Previously, a similar method was used to determine interstellar H atom and proton number densities by Lallement (1996), Gloeckler et al. (1997), Izmodenov et al. (2003). With these constraints we find that the heliospheric interface model with $\mathrm{n}_{H,LIC} = 0.18 \pm 0.02$ cm^{-3},

n$_{p,LIC}$ = 0.06 ± 0.015 cm^{-3} and n$_{He^+,LIC}$ = 0.009 cm^{-3} provides the best fit to SWICS Ulysses pickup hydrogen data. The interstellar hydrogen ionization fraction derived from our results is in agreement with recent calculations of the photo-ionization of interstellar matter within 5 pc of the Sun (Slavin and Frisch, 2002).

The total density and pressure of the interstellar gas are calculated to be:

$$\rho_{LIC} = m_p n_{p,LIC} + m_{He} n_{He^+,LIC},$$

$$p_{LIC} = 2(n_{p,LIC} + n_{He^{++},LIC})kT_{LIC}.$$

4. Results

To evaluate possible effects of both interstellar ions of helium and solar wind alpha particles we performed parametric model calculations with eight different sets of boundary conditions given in Table 1. Calculated locations in the upwind direction of the termination shock, the heliopause and the bow shock are given for each model in the last three columns of Table 1 respectively. In the first six models we assume that n$_{p,LIC}$ = 0.06 cm^{-3} and n$_{H,LIC}$ = 0.18 cm^{-3}. Model 1 does not include either interstellar ionized helium or solar wind alpha particles. Effects of interstellar ionized helium can be seen by comparing results of model 1, with no ionized interstellar He, and model 2, where 37.5 % ionization of interstellar helium is assumed. Interstellar helium ions increase the interstellar dynamic pressure by 60 % and the interstellar thermal pressure by 15 % in model 2 as compared with model 1:

$$\frac{(\rho v^2)_{LIC,model2}}{(\rho v^2)_{LIC,model1}} = \frac{n_{LIC,p} + 4n_{LIC,HE^+}}{n_{LIC,p}} = 1.6,$$

$$\frac{p_{LIC,model2}}{p_{LIC,model1}} = \frac{n_{LIC,p} + n_{LIC,HE^+}}{n_{LIC,p}} = 1.15.$$

This additional interstellar pressure pushes the bow shock, the heliopause and the termination shock towards the Sun, from the dashed to the solid curves of Figure 1. In model 2 the heliopause is ∼20 AU, and the termination shock ∼7 AU closer to the Sun as compared with model 1. The influence on the bow shock location is even stronger. The BS is ∼50 AU closer to the Sun as compared with model 1. This strong displacement of the bow shock toward the Sun is also connected with the fact that the Mach number is larger when ionized helium is taken into account. Indeed,

$$M = \frac{V}{\sqrt{\gamma P/\rho}} = V\sqrt{\frac{n_{p,LIC} + 4n_{He^+,LIC}}{n_{p,LIC} + n_{He^+,LIC}} \frac{m_p}{2k_B T_{LIC}}} = 2.3,$$

as compared to M=1.97 for model 1. Here m_p, k_B are the proton mass and the Boltzmann's constant, respectively. The plasma compression at the bow shock is 1.45 for model 2 and 1.22 for model 1. Higher compression of the interstellar plasma at the bow shock and the corresponding reduction of the size of the outer heliosheath - the distance between the bow shock and the heliopause - make the optical depth for interstellar H atoms in the interface about the same for all models 1-6. The resulting filtration of interstellar hydrogen atoms in the interface is therefore about the same in all of the first six models. The effects of the solar wind alpha particles are seen from comparison of results of model 1 with model 3. Influence of solar wind alpha particles on the locations of the heliopause and shocks is opposite to the influence of interstellar helium ions discussed above. Since solar wind alpha particles constitute only 10 - 18 % of the solar wind dynamic pressure, their influence is less pronounced. The heliopause and the termination shock move out by $\sim$6 AU and $\sim$5 AU from the Sun, respectively.

The net effect of both the interstellar ionized helium and solar wind alpha particles is seen by comparing models 4-6. Model 5 corresponds to 37.5 % of the interstellar helium ionization, and 2.5 % the solar wind alpha particles abundance. The influence of interstellar helium ions on the locations of HP, BS, and TS is stronger than the influence of the solar wind alpha particle component. The heliopause is located $\sim$ 13 AU closer to the Sun in model 5 than model 1. We note with interest that Gurnett et al. (1993, 1995) analyzing heliospheric radio emission events of 1983-84 and 1992-94 at plasma cutoff frequency, fp = 2.2 to 2.8 kHz detected by Voyagers estimated the average distance to the heliopause to be 158 AU, close the HP distance we find for model 5. The bow shock is closer to the Sun by $\sim$40 AU. At the same time the termination shock location is only $\sim$2 AU closer to the Sun. For smaller interstellar He ionization (model 4) or a higher abundance of solar wind alpha particles (model 6) the termination shock is 4-5 AU further from the Sun as compared to model 5. To estimate the influence of the interstellar ionized helium component in the case of smaller hydrogen ionization, we took $n_{p,LIC}$ =0.04 cm^{-3} and $n_{H,LIC}$ = 0.20 cm^{-3} in models 7 - 8. Expectedly, the effect on the locations of the heliopause and termination shock is about the same as previously (see table 1). The bow shock is $\sim$50 AU closer in model 8 as compared to model 7.

5. Implications on the TS Location

Using our model and boundary conditions described above, we performed parametric studies by varying the interstellar proton and hydrogen atom number densities in the ranges of 0.03-0.1 cm^{-3} and 0.16-0.2 cm^{-3}, respectively. The interstellar helium ion number density

was calculated by using an interstellar helium atom number density of 0.015 cm^{-3} and 10 for the interstellar H/He ratio. Figure 2 shows results of our calculations. Displayed are contour isolines of (1) the neutral hydrogen density at the TS, (2) the LIC helium ionization fraction, and (3) the termination shock location in the upwind direction on a ($n_{H,LIC}$,$n_{p,LIC}$)-coordinate plane. Dashed areas show (a) the $n_{H,TS}$ range of 0.095 - 0.105 cm^{-3}, which corresponds to recent Ulysses determination (Gloeckler and Geiss, 2002); (b) the interstellar helium ionization fraction range of 0.3 -0.4 derived from line-of-sight EUVE measurements toward white draft stars in the LSIM (Wolff et al., 1999). The intersection of the two dashed areas gives a likely range of interstellar proton and atomic hydrogen number densities compatible with observations. Using long-term averages of IMP 8 solar wind parameters places the average termination shock location at more than 90 AU in the upwind direction and more than 95 AU in the direction of Voyager 1 for all pairs of ($n_{H,LIC}$,$n_{p,LIC}$) in this doubly-dashed area. Solar-cycle variations of the solar wind ram pressure lead on average to a 7 to 8 AU deviation of the termination shock distance around its mean value (Izmodenov, et al., 2003). In 2002 the termination shock had its minimal location (Izmodenov et al., 2003), which according to our model calculations should not have been less than 87-88 AU under average solar wind conditions at that time of the solar cycle. Based on measurements of low energy particle fluxes, spectra and composition by the Voyager-1/LECP instrument, and of indirect determination of the solar wind speed using particle anisotropy measurements Krimigis et al. (2003) reported the probable crossing of the termination shock by Voyager-1 at 85 AU in the summer of 2002 and return to the TS upstream region about six months later. Temporary and probably localized excursions of the termination shock inward by a few AU beyond our minimum value cannot be ruled out by our calculations, since they could result from an anomalously low solar wind ram pressure and possibly other causes. However, should future measurements show that the TS location is consistently less than what we calculate here, then a revision of the LIC He ionization to higher values and or a stronger local interstellar magnetic field may be required.

6. Summary and conclusions

We studied the influence of the interstellar ionized helium component on the heliospheric interface for the first time. This component may create up to 50 % of total dynamic pressure of the interstellar ionized component. It is shown the heliopause, termination and interstellar bow shocks are closer to the Sun when influence of interstellar helium ions is taken into account. This effect is partially compensated by additional solar wind alpha particle pressure that we also took into account in our model. The net result is as follows: the heliopause, termination and bow shocks are closer to the Sun by ∼12 AU, ∼ 2 AU, ∼ 30 AU, respectively

in the model taking into account both interstellar helium ions and solar wind alpha particles (model 5) as compared to the model ignoring these ionized helium components (model 1). We also found that both interstellar ionized helium and solar wind alpha particles do not influence the filtration of the interstellar H atoms through the heliospheric interface.

We use our model to determine a plausible range of ($n_{H,LIC}$,$n_{p,LIC}$) compatible with (1) $n_{H,TS} = 0.1 \pm 0.05$ cm^{-3} determined by Ulysses/SWICS, (2) ionization of interstellar helium 0.35 $\pm$0.05. Using our model we found that the lower limit (1-σ) of the termination shock location in the direction of Voyager-1 is 88 AU. While temporary and localized motions of the termination shock position as close as 85 AU cannot be ruled out, definitive experimental determination of the average termination shock location in the near future would place a firm additional constraint on the possible ranges of interstellar parameters.

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Table 1: Sets of model parameters and locations of the TS, HP and BS in the upwind direction

#	$n_{H,LIC}$	$n_{p,LIC}$	$\frac{n_{\alpha,sw}}{n_{e,sw}}$	χ_{He}[a]	R(TS)	R(HP)	R(BS)
	cm^{-3}	cm^{-3}	%		AU	AU	AU
1	0.18	0.06	0	0	95.6	170	320
2	0.18	0.06	0	0.375	88.7	152	270
3	0.18	0.06	2.5	0	100.7	176	330
4	0.18	0.06	2.5	0.150	97.5	168	310
5	0.18	0.06	2.5	0.375	93.3	157	283
6	0.18	0.06	4.5	0.375	97.0	166	291
7	0.20	0.04	0	0	95.0	183	340
8	0.20	0.04	2.5	0.375	93.0	171	290

[a] $\chi_{He} = HeII/(HeI + HeII)$

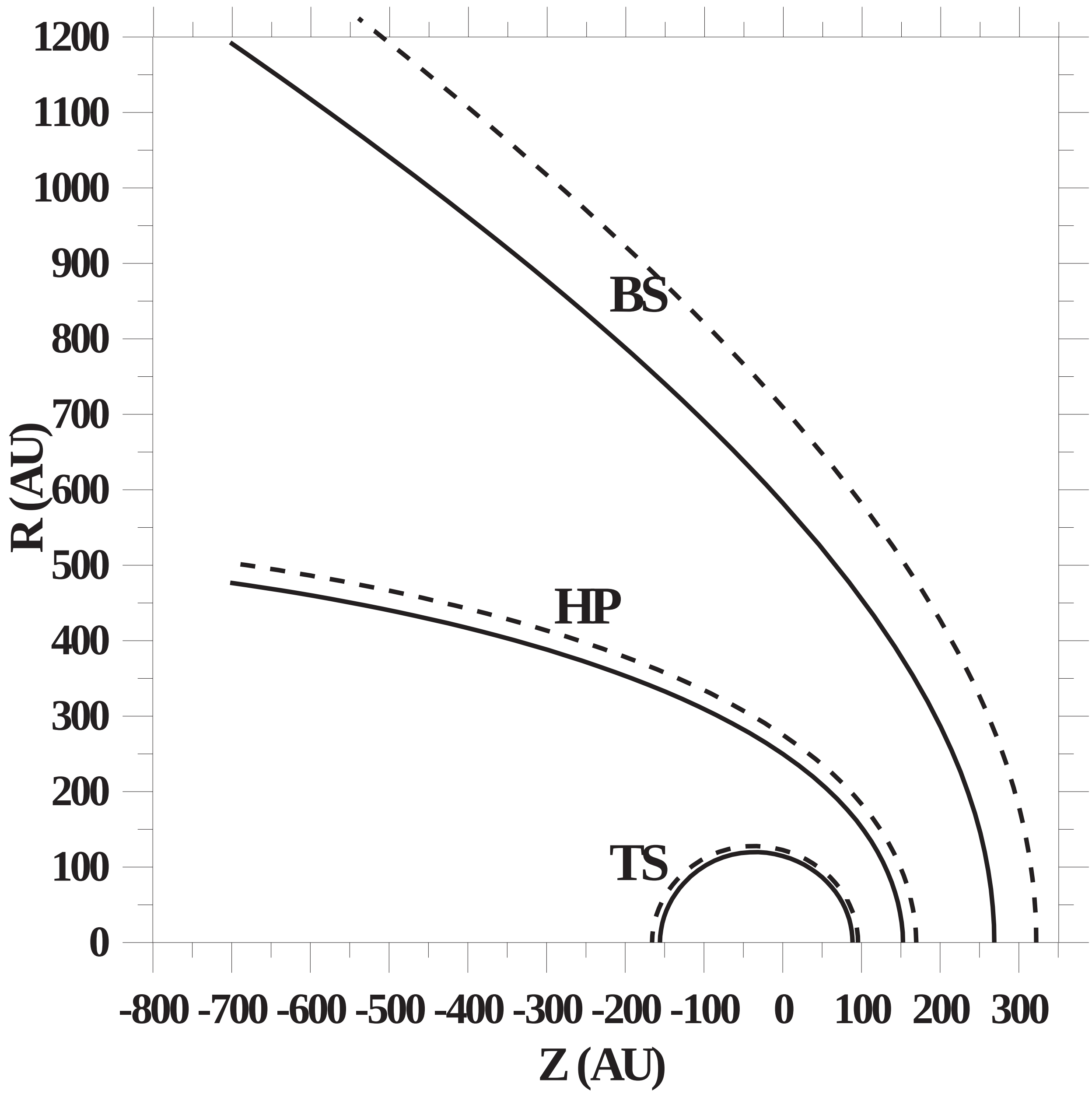

Fig. 1.— Sketched is the idealized structure of the heliospheric interface (the region of interaction of the solar wind with the LIC) based on results of numerical modeling. We used the following interstellar parameters: (a) atomic hydrogen number density (= 0.18 cm^{-3}), (b) proton number density (= 0.06 cm^{-3}), (c) gas temperature (= 6500 K), and (d) gas speed (relative to the Sun) (= 26.4 km/s), and average solar wind parameters: (e) solar wind density at 1 AU (= 7.39 cm^{-3}), and (f) speed (= 432 km/s). Discussion of, and references for the chosen parameters are given in the text. Dashed curves correspond to model 1, solid curves correspond to model 2 (see, Table 1).

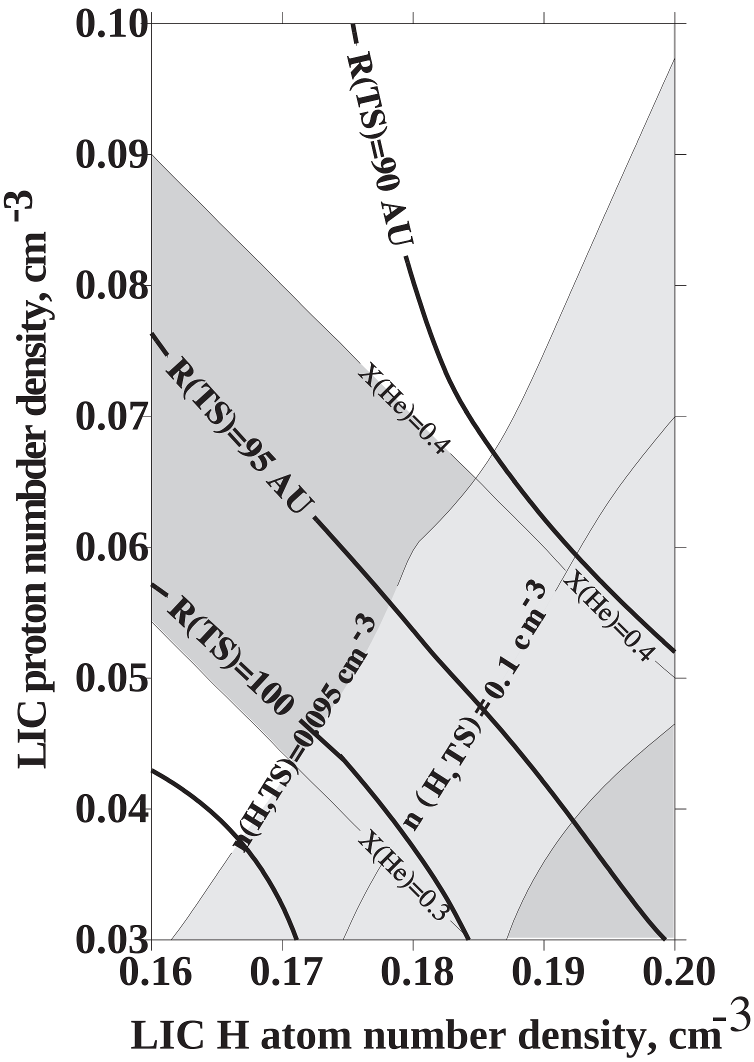

Fig. 2.— Contour plots of the interstellar H atom number density at the termination shock, the LIC helium ionization fraction, and the termination shock location in the upwind direction.